CONTROL OF MACPHERSON ACTIVE SUSPENSION SYSTEM USING SLIDING MODE CONTROL WITH COMPOSITE NONLINEAR FEEDBACK TECHNIQUE

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To my beloved wife Miza and childs...........

Aina, Imanina, Irdina, and Aminul Fatih.

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ABSTRACT

The MacPherson active suspension system is able to support the weight of vehicle and vibration isolation from road profile, and is also able to maintain the traction between tyre and road surface. It also provides both additional stability and maneuverability by performing active roll and pitch control during cornering and braking, and the most significant are ride comfort and road handling performance. However, a drawback of MacPherson model is the self-steer phenomenon in the active suspension system. The problem might be solved by controlling the actuator force and control arm of the system. The MacPherson model has a similar layout to a real vehicle active suspension system. The mathematical model of the system produces a nonlinear mathematical model with uncertainties. Therefore, the proposed control strategy must be able to cater the uncertainties in mathematical model and simultaneously provide a fast response to the system. The control strategy combines Composite Nonlinear Feedback (CNF) algorithm and Proportional Integral Sliding Mode Control (PISMC) algorithm to achieve quick response and to reduce uncertainties. Optimisation of parameters in the CNF was performed using Evolutionary Strategy (ES) algorithm for fast transient performance. Thus, the controller is called Proportional Integral Sliding Mode Control – Evolutionary Strategy – Composite Nonlinear Feedback (PISMC-ES-CNF). To validate the proposed controller, the conventional Sliding Mode Control (SMC) and CNF were utilised to control the system under various road profiles. The ISO 2631-1, 1997 was used as a reference of ride comfort level for the acceleration of sprung mass. Results show that the proposed controller, PISMC-ES-CNF achieved the best control performance under various road profiles. The results obtained also prove that the PISMC-ES-CNF managed to improve ride comfort quality and road handling quality and has also delivered better control performance in terms of transient response of acceleration of sprung mass, reducing overshoot and chattering problem compared to conventional SMC and CNF.

ABSTRAK

Sistem gantungan aktif kenderaan MacPherson berkeupayaan untuk menyokong berat kenderaan, pengasingan getaran berdasarkan profil jalan dan untuk mengekalkan cengkaman antara tayar dan permukaan jalan raya. Ia juga menyediakan kestabilan tambahan dan pergerakan dengan melakukan gelekan dan kawalan anggul aktif semasa membelok dan membrek, dan yang lebih penting ialah keselesaan pemanduan dan prestasi pengendalian jalan raya. Walau bagaimanapun, kelemahan model MacPherson adalah fenomena mengemudi-diri yang berlaku dalam sistem gantungan aktif. Model MacPherson mempunyai susun atur yang sama dengan sistem gantungan aktif kenderaan sebenar. Pemodelan matematik sistem menghasilkan model matematik tak linear dengan ketidaktentuan. Oleh itu, strategi kawalan yang dicadangkan mesti berupaya untuk menampung dalam ketidaktentuan dalam model matematik dan pada masa yang sama memberikan tindak balas yang cepat kepada sistem. Strategi kawalan menggabungkan algoritma pengawal Suap Balik Tak linear Komposit (CNF) dan algoritma pengawal Mod Gelangsar Kamiran Berkadaran (PISMC) untuk mencapai prestasi sambutan cepat dan mengurangkan ketidaktentuan. Pengoptimuman parameter dalam CNF dilakukan dengan menggunakan algoritma Strategi Evolusi (ES) untuk prestasi fana cepat. Oleh yang demikian, pengawal ini dikenali sebagai Mod Gelangsar Kamiran Berkadaran – Strategi Evolusi – Suap Balik Tak Linear Komposit (PISMC-ES-CNF). Untuk mengesahkan pencapaian pengawal yang dicadangkan, Pengawal Konvensional Mod Gelangsar (SMC) dan CNF telah digunakan dalam mengawal sistem untuk profil permukaan jalan raya yang pelbagai. ISO 2631-1 1997 digunakan sebagai rujukan pada tahap keselesaan perjalanan yang berkualiti untuk pecutan jisim terpegas. Keputusan menunjukkan bahawa cadangan kawalan, PISMC-ES-CNF telah mencapai prestasi kawalan terbaik pada pelbagai jenis permukaan jalan. Hasil kajian juga membuktikan bahawa PISMC-ES-CNF telah meningkatkan keselesaan perjalanan yang berkualiti dan pengendalian jalan yang berkualiti serta memberikan prestasi kawalan yang lebih baik dari segi sambutan fana untuk pecutan jisim terpegas, mengurangkan terlajak, dan mengurangkan masalah gelatukan berbanding dengan SMC konvensional dan CNF.

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LIST OF ABBREVIATIONS

2-DOF	-	two-degree-of-freedom
ANOVA	-	analysis of variance
BP	-	backpropagation
ES	-	evolutionary strategy
CNF	-	composite nonlinear feedback
CTL	-	central limit theorem
GOF	-	goodness of fit
HIL	-	hardware in the loop
HSRFBNC	-	hybrid self-organizing fuzzy radial basis-function neural network controller
ISMC	-	integral sliding mode control
ISO	-	international standard organization
LMI	-	linear matrix inequalities
LPV	-	linear parameter varying
LQR	-	linear quadratic regulator
MIL	-	model in the loop
MIMO	-	multi input multi output
MCS	-	monte carlo simulation

NFWN	-	neuro-fuzzy wavelets network
NN	-	neural network
PDF	-	probability distribution function
PID	-	proportional integral derivative
PIL	-	processor in the loop
PISMC	-	proportional integral sliding mode control
PSD	-	power spectral density
PSO	-	particle swarm optimization
SIL	-	software in the loop
SMC	-	sliding mode control
SOFC	-	self-organizing fuzzy controller
STC	-	super twisting control
VSCS	-	variable structure control system

LIST OF SYMBOLS

f_a	-	actuator force
m_s	-	mass of the car body
m_u	-	mass of the car wheel
k_s	-	stiffness of the car body spring
k_t	-	stiffness of car tyre
c_p	-	damper coefficient
l_A	-	distance from point 0 to A
l_B	-	distance from point 0 to B
l_C	-	distance from point 0 to C
f_b	-	weight of human body
Z_s	-	displacement of sprung mass
$\dot{Z}_s$	-	velocity of sprung mass
$\ddot{Z}_s$	-	acceleration of sprung mass
θ_0	-	initial angular displacement of control arm
θ	-	angular displacement of control arm
$\dot{\theta}$	-	angular velocity of control arm
$\ddot{\theta}$	-	angular acceleration of control arm

Z_r	-	displacement of road profile
c_{p1}	-	the linear damping coefficient
c_{p2}	-	the nonlinearity damping coefficient
k_{s1}	-	the linear stiffness of car body spring
k_{s2}	-	the nonlinearity stiffness of car body spring
Δm_s	-	the uncertainty of sprung mass
Δk_t	-	the uncertainty of stiffness of car tyre
Δc_{p1}	-	the uncertainty of linear damping coefficient
Δc_{p2}	-	the uncertainty of nonlinearity damping coefficient
Δk_{s1}	-	the uncertainty of linear stiffness of car body spring
Δk_{s2}	-	the uncertainty of nonlinearity stiffness of car body spring
Δf_m	-	the matched uncertainties
Δf_u	-	the unmatched uncertainties
ρ	-	nonlinear function of CNF
$\hat{x}$	-	the error between actual state and desired state
α	-	tuning parameter in nonlinear function of CNF
β	-	tuning parameter in nonlinear function of CNF
ζ	-	steady state damping ratio
φ_1	-	sliding gain of PISMC
μ	-	the thickness boundary layer of PISMC
C_{pk}	-	measuring process capability
σ_{qMP}	-	sliding surface of PISMC

I_n	-	an $n \times n$ identity matrix
$D^C(\psi)$	-	denotes as the disc centred at the starting point.
e	-	current error backpropagation in neural network
y_d	-	desired output in neural network
y_a	-	current output at iteration-k
w_{ij}	-	weight in Levenberg-Marquardt (LM) algorithm
μ_1	-	learning rate in LM algorithm
θ_{ss}	-	a width of band sliding surface in ISMC
η	-	reachability condition in ISMC
α_1	-	controller parameter in ISMC

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CHAPTER 1

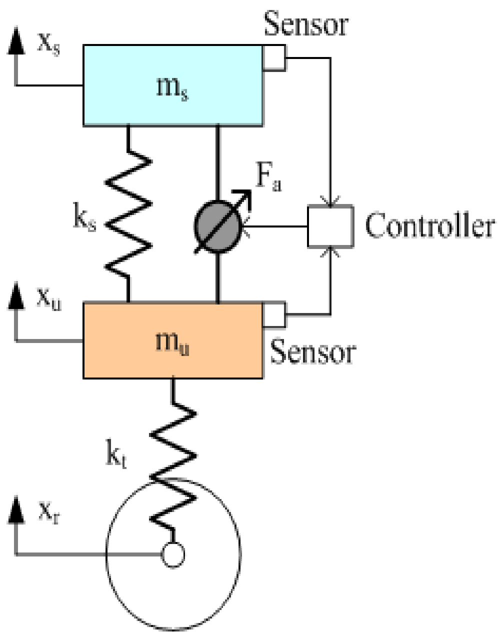
INTRODUCTION

1.1 Introduction to Active Suspension System

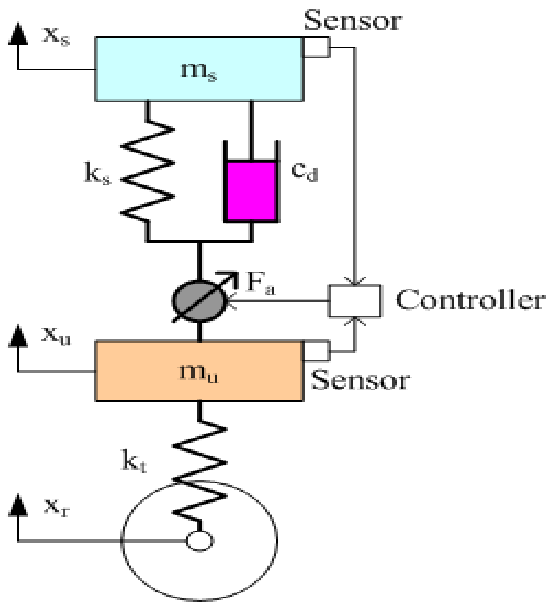
A vehicle passive suspension system usually involves springs and shock absorbers that aid in isolating the vehicle chassis and passenger from unexpected vertical displacements of the wheel assemblies while driving; the phenomenon is called ride comfort performance. Meanwhile, active suspension is composed of an actuator and a mechanical spring, or an actuator, and a damper, Xue *et al.* (2011).

Another important purpose of vehicle suspension is to maintain a secure interaction between the road and the tyres, as well as to offer guidance along the road profiles. This capability is known as handling performance. The active suspension can be classified into two types of bandwidths. The high-bandwidth active suspension controls both the sprung mass, m_s, and the unsprung mass, m_u if the active actuator works mechanically in parallel with the spring as illustrated in

Figure 1.1(a). On the hand, the low-bandwidth active suspension controls the sprung mass if the active actuator works mechanically in series with the spring and the damper as portrayed in Figure 1.1(b). The F_a is refers to the actuator force, k_s is stiffness of the car body spring, k_t stiffness of car tyre, and C_d damper coefficient. Other than that X_s, X_u, and X_r are state variables for sprung mass, unsprung mass, and road profile. Generally, the frequency of the unsprung mass lies in the range of 10-15 Hz, while the frequency of the sprung mass lies in the range of 1-2 Hz. (Xue *et al.* 2011, Appleyard and Wellstead 1995). Moreover, active suspensions commercially implemented in automobiles today are based on hydraulic or pneumatic actuator, Appleyard and Wellstead (1995). Figure 1.2 shows the schematic diagram of the MacPherson strut suspension system applied in modern automotive active suspension system. (Hong *et al.* 1999). The f_d is a body force of human, m_u reflects the unsprung mass, m_s is sprung mass, and Z_s refers to displacement of sprung mass. If the joint between the control arm and the car body is assumed to be a bushing and the mass of the control arm is not neglected, the degrees of freedom of the whole system are four. The generalised coordinates in this case are Z_s, *d,* θ_1, and θ_2. However, if the mass of the control arm is ignored and the bushing is assumed to be a pin joint, then the degrees of freedom will becomes two. In fact, the typical independent type of MacPherson suspension system consists of wheel assembly connected to the tyre, lower arm connecting to the chassis and the wheel assembly, tie rod for the steering, and strut involving the spring-damper system that absorb shock from the road surface.



(a)



(b)

Figure 1.1: Quarter car linear model active suspension system: (a) High-bandwidth, and (b) Low-bandwidth in Xue *et al.,* (2011).

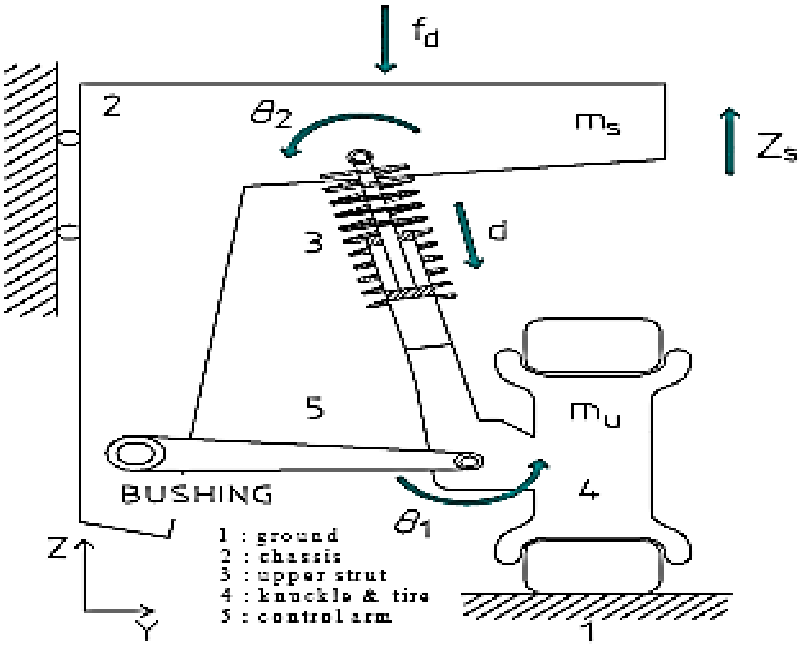


Figure 1.2: A schematic diagram of the MacPherson suspension system for quarter car model in Hong *et al.,* (1999).

1.2 Research Background

Designing active suspension control strategies is indeed a major challenge in relation to automotive control problem. The control problems are related to ride comfort, body motion, road handling and suspension travel. Ride comfort is directly associated to the acceleration of sprung mass based on the degree of comfort. Meanwhile, body motion refers to bounce, pitch, and roll of sprung mass are generated by cornering, acceleration, or deceleration manoeuvre. Next, road handling reflects the contact forces of tyres and the road surface; whereas suspension travel refers is displacement between a sprung mass and an unsprung mass. Therefore it is inspiring issue for one active suspension system to simultaneously optimize all four sets of parameters.(Hrovat, 1997, Appleyard and Wellstead, 1995, Xue *et al.,* 2011).

Furthermore, the modern automotive suspension system can be classified as passive, semi-active and active suspensions systems as presented in Figure 1.3. Passive suspension consists of spring and damper connected in parallel with each other, whereas semi-active suspension is comprised of adjustable damper and spring in parallel. Meanwhile, active suspension system is made of spring, damper, and actuator.

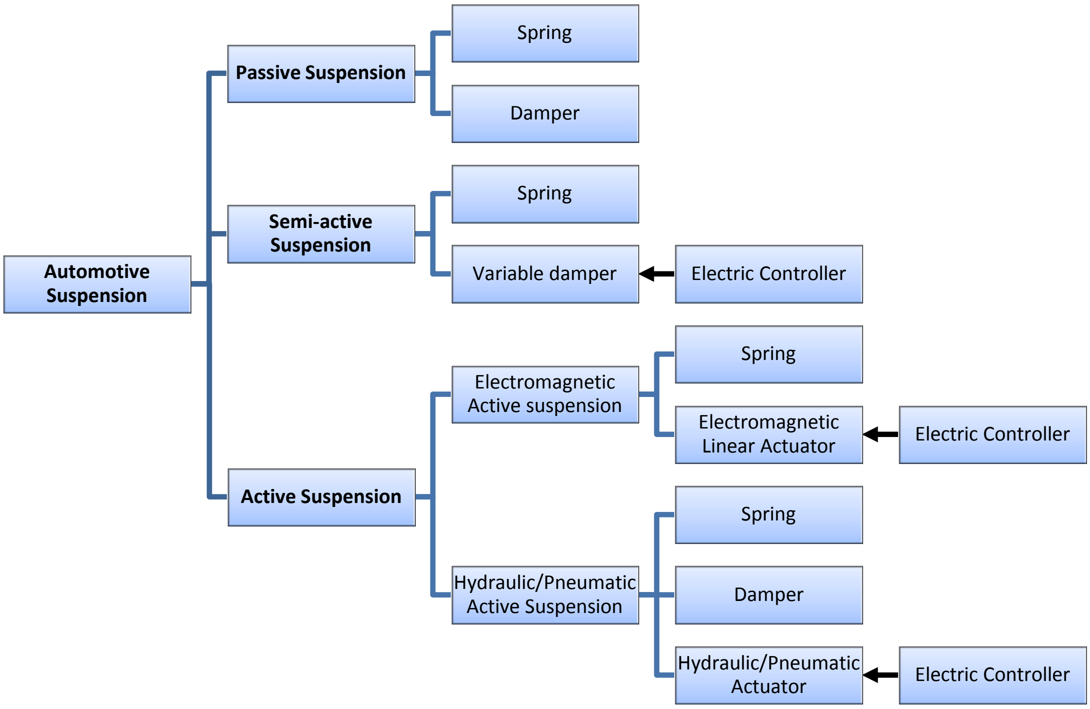


Figure 1.3: Classification of modern automotive suspension in Xue *et al.* (2011)

In addition, researches over the past five decades have shown that a linear optimal control scheme offers an effective method in designing active suspension control strategies that can improve both vehicle ride and handling performance simultaneously, Hrovat (1997). In fact, most researchers focused on active suspension system with a linear model without uncertainties. However, a modern active suspension system is characteristically nonlinear and uncertain especially for the MacPherson active suspension system.

1.3 Problem Statement

Most previous researches concerning automotive have employed the linear model of active suspension system (Hrovat 1990, 1997, Xue *et al.,* 2011). In this model the spring, the damper and the actuators were arranged in a 90 degree vertical arrangement. The new model of the MacPherson suspension has been proposed by (Hong *et al.,* 1999, and Fallah *et al,.* 2008). In this new model the spring, the damper and the actuators were not arranged in 90 degree vertical where this phenomenon created a nonlinear characteristics. However, the number of studies from previous researchers did not consider the issues pertaining to uncertainties, and nonlinearities in the parameters of MacPherson active suspension system. Furthermore, the self-steer that takes place in the MacPherson active suspension system causes unbalanced tyre forces and moments, suspension geometry, as well as unbalanced force line position, Nishizawa *et al.* (2006). The vertical acceleration of sprung mass and the angular acceleration of the control arm in the MacPherson strut are the parameters have been applied to minimize the self-steer. The self-steer, hence, can be minimized by controlling the angular acceleration of the control arm in the MacPherson strut. Therefore, a robust control strategy is essential to control the MacPherson active suspension system due to its nonlinear, uncertain and self-steer characteristics toward achieving a virtuous measurement on ride comfort and road handling performances.

In conjunction to that, the Composite Nonlinear Feedback (CNF) control technique is a fast and a smooth tracking performance. The CNF consists of both linear feedback and nonlinear feedback laws. The linear feedback part is designed to yield a closed-loop system with a small damping ratio for a quick response, while the nonlinear feedback part is used to increase the damping ratio of the closed-loop system as the system output approaches the target reference to reduce the overshoot caused by the linear part. Besides, the PISMC controller is used to reject disturbance and zero steady state error while the proportional part removes the uncertainty. Therefore, the study utilised the CNF to achieve high performance saturated actuator and the PISMC to ensure invariance against disturbances, uncertainties, nonlinearities, and zero steady state error. The parameters of α and β of nonlinear function in CNF had been optimized by using Evolutionary Strategy (ES) for better control performance in transient response for MacPherson active suspension system. The ES algorithm was used for optimization of nonlinear function in CNF.

1.4 Research Objectives

This research had enhanced and improved the performance of the Macpherson active suspension systems using a robust controller. The specific objectives of the research are given in the followings:

(i) To establish a nonlinear mathematical model based on the MacPherson suspension system.

(ii) To design a Proportional Integral Sliding Mode Control with Composite Nonlinear Feedback (PISMC-CNF) strategy that is able to improve the ride comfort and the road handling performances.

(iii) To evaluate the effectiveness of the proposed controller for ride comfort and road handling performance enhancement by using MATLAB/Simulink.

1.5 Scope of Research Work

The scope of work focused on the mathematical model of the MacPherson active suspension system, as well as the control performance analysis of the system by using MATLAB/Simulink and Minitab. Moreover, the numerical experiment was performed to execute the validation process on the MacPherson active suspension system. The scopes of this research are provided in the followings:

(i) The main elements of mathematical modeling of the MacPherson active suspension system consisted of displacement of sprung mass, Z_s , velocity of sprung mass, $\dot{Z}_s$, and acceleration of sprung mass, $\ddot{Z}_s$. These elements are related to the ride comfort performance. The angular displacement of the control arm, θ, the angular velocity of the control arm, $\dot{\theta}$, and the angular acceleration of the control arm, $\ddot{\theta}$ are related to the road handling performance. These elements are also known as unsprung mass.

(ii) The type of actuator force f_a is not discussed in detail in term of mathematical modeling. Some examples of the actuator force f_a are hydraulic actuator, pneumatic actuator, and electromagnetic actuator.

(iii) Only vertical displacement for the sprung mass Z_s had been used in this model.

(iv) Parameter θ is the angular displacement of the control arm. The link of θ to the car body is deliberated as an unsprung mass.

(v) The values of vertical displacement and control arm were measured from the static equilibrium point.

(vi) The sprung and the unsprung masses had been assumed to be two different elements which, reflected ride comfort and road handling.

(vii) The mass and the control arm stiffness were ignored.

(viii) The forces were in the linear region for spring deflection, tyre deflection and damping forces.

(ix) At interaction patch between tyre and ground, with no moment was applied.

(x) The analysis of acceleration of sprung mass referred to the RMS vertical acceleration level and degree of comfort based on ISO2631-1, 1997. The analysis was carried out based on the control performance applied in the MacPherson active suspension system.

(xi) The quarter car model of MacPherson active suspension had been employed for this research work.

(xii) Most D Class cars are equipped with dynamic suspension system. Therefore it was selected for this research work.

(xiii) The road profiles used in mathematical simulation and numerical experimental were Bounce Sine Sweep road, Chassis Twisted road and Large Smooth Bump road.

(xiv) The conventional Sliding Mode Control (SMC) and the CNF were only used to be compared with the proposed controller in analysing the control performance in the system.

(xv) An optimization is of a nonlinear control law of CNF was performed by using the Evolutionary Strategy (ES) only.

(xvi) Statistical data analysis was only applied for acceleration of sprung mass. Some tools of statistical data analysis are process capability and one way analysis of variance. In fact, a software programme known as Minitab was used.

1.6 Contributions of Research Work

Over these recent years, the issue pertaining to active suspension system has been related to attain the best ride comfort and road handling performance. Thus the main objective of any proposed controller is to reduce the effect of the road profiles and to ensure the stability of the vehicle during the manoeuvres. Hence, the main contributions of this research are listed in the followings:

(i) A new robust control strategy based on the Proportional Integral Sliding Mode Control and Composite Nonlinear Feedback (PISMC-CNF) that successfully improved the ride comfort and the road handling performance of the MacPherson active suspension system.

(ii) A new method was discovered for optimizing the values of sliding gain, boundary layer thickness, as well as the value of α and β in nonlinear function of PISMC-CNF by using Evolutionary Strategy (ES). The neural network was utilised to search the matrix of C_{qMP} in PISMC-CNF.

1.7 Structure and Layout of the Thesis

The thesis presents the implementation of the mathematical modeling of MacPherson active suspension system and the designs of control strategy for the system.

Chapter 2 highlights of the literature review, which presents the overview of active suspension system and the recent control strategies employed. This chapter further describes previous researches concerning vehicle suspension system mathematical modeling. The control strategies applied such as linear control, nonlinear control, and intelligent control are also reviewed.

Chapter 3 presents the details of the MacPherson active suspension system mathematical modeling. Two degrees of freedom (2-DOF Quarter Car Model) has been modelled for active and passive suspension system. The details of the physical parameters employed for both numerical simulation and numerical experiment are highlighted in this chapter. Besides, some issues related to uncertainties and nonlinearities of the MacPherson active suspension system are looked into as well.

Chapter 4 presents the overview of the Composite Nonlinear Feedback (CNF) and the Sliding Mode Control (SMC) control theories. The properties of CNF are explained in detail. The components of CNF are both linear and nonlinear control laws. Applications of the CNF in past years are reviewed in this chapter. In fact, the point of view for control theory pertaining to SMC is explained. Furthermore, matched and unmatched cases, as well as some issue of the chattering problem, are discussed. Moreover, a particular application of the SMC in past research work is explained.

Chapter 5 presents a new control strategy for the MacPherson active suspension system. Proportional Integral Sliding Mode Control Evolutionary Strategy Composite Nonlinear Feedback (PISMC-ES-CNF) is proposed to overcome the uncertainties, as well as to achieve acceptable ride comfort and road handling performance. The details of the controller design are explained in this chapter. Overall the results obtained are discussed in this chapter. The stability and the reachability conditions of both sliding surface and those controlled are also discussed. Furthermore, optimization of the related parameters performed by using the ES method is presented.

Finally, Chapter 6 depicts the conclusion of the research work and future work.

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